SCIENCE

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THE CONSTRUCTION OF THE HEAVENS[1]

ALTHOUGH at the present time our minds are largely absorbed by the war, the meeting of the British Association in Manchester indicates that we consider it right to make our annual review of scientific progress. I shall therefore make no apology for choosing the same subject for my address as I should have chosen in other circumstances. It is a subject far removed from war, being an account of the manner in which astronomers have with telescopes and spectroscopes investigated the skies and the conclusions they have reached on what Herschel called "The Construction of the Heavens."

Our knowledge of the fixed stars, as they were called by the old astronomers, is of comparatively recent origin, and is derived from two sources: (1) the measurement of small changes in the positions of the stars in the sky, and (2) the analysis of the light received from them and the measurement of its amount. To this end the numerous instruments of a modern observatory have been devised. The desire to examine fainter objects, and still more the necessity of increasing the accuracy of observations, has brought about a continuous improvement in the range and accuracy of astronomical instruments. Methods which had been perfected for observations of a few stars have been extended so that they can be applied to a large number. For these reasons the progress of sidereal astronomy may seem to have gone on slowly for a time. The more rapid progress of recent years arises

[1] Address of the President of the Section of Mathematics and Astronomy at the Manchester meeting of the British Association for the Advancement of Science.

from the accumulation of data, for which we are indebted to generations of astronomers, and from the gradual increase in power and perfection of our instruments.

The first insight into the stars as a whole naturally came from the survey of their numbers and distribution; and Herschel, who constructed the first great telescopes, explored the heavens with untiring skill and energy, and speculated boldly on his observations, is justly regarded as the founder of sidereal astronomy. In his great paper "On the Construction of the Heavens," Herschel gives the rules by which he was guided, which I should like to quote, as they may well serve as a motto to all who are engaged in the observational sciences:

> But first let me mention that if we would hope to make any progress in an investigation of this delicate nature we ought to avoid two opposite extremes of which I can hardly say which is the most dangerous. If we indulge a fanciful imagination and build worlds of our own, we must not wonder at our going wide from the path of truth and nature; but these will vanish like the Cartesian vortices, that soon gave way when better theories were offered. On the other hand, if we add observation to observation, without attempting to draw not only certain conclusions but also conjectural views from them, we offend against the very end for which only observations ought to be made. I will endeavor to keep a proper medium; but if I should deviate from that I could wish not to fall into the latter error.

In this spirit he discussed the "star gauges" or counts of stars visible with his great reflector in different parts of the sky, and concluded from them that the stars form a cluster which stretches to an unknown but finite distance, considerably greater in the plane of the Milky Way than in the perpendicular direction. He gave this distance as 497 times that of Sirius. He did not hesitate to advance the theory that some of the nebulæ were similar clusters of stars, of which that in Andromeda, judging from its size, was the nearest. Herschel had no means of telling the scale of the sidereal system, though he probably supposed the parallax of Sirius to be of the order of 1″.

Though some of the assumptions made by Herschel are open to criticism, the result at which he arrived is correct in its general outline. I shall attempt to give a brief account of some of the principal methods used to obtain more definite knowledge of the extent and constitution of this "island universe." The stars of which most is known are, in general, those nearest to us. If the distance of a star has been measured, its coordinates, velocity perpendicular to the line of sight, and luminosity are easily found. In the case of a double star the orbit of which is known the mass may also be determined. But only a very small proportion of the stars are sufficiently near for the distance to be determinable with any accuracy. Taking the distance corresponding to a parallax of 1″ or the parsec as unit—*i. e.*, 200,000 times the distance of the earth from the sun—fairly accurate determinations can be made up to a distance of 25 parsecs, but only rough ones for greater distances.

For much greater distances average results are obtainable from proper motions, and the mean distances of particular classes of stars—for instance, stars of a given magnitude or given type of spectrum—can be found with confidence up to a distance of 500 parsecs, and with considerable uncertainty to twice this distance. The density of stars in space as a function of the distance, the percentage of stars within different limits of luminosity, the general trend of the movements of stars and their average velocities can also be found, within the same limits of distance.

For all distances, provided the star is sufficiently bright, its velocity to or from the earth can be measured. The general

consideration of these velocities supplies complementary data which can not be obtained from proper motions, and confirms other results obtained by their means. For distances greater than 1,000 parsecs our knowledge is generally very vague. We have to rely on what can be learned from the amount and color of the light of the stars, and from their numbers in different parts of the sky.

PARALLAX

Let us begin with the portion of space nearest to us, within which the parallaxes of stars are determinable. The successful determination of stellar parallax by Bessel, Struve and Henderson in 1838 was a landmark in sidereal astronomy. The distances of three separate stars were successfully measured, and for the first time the sounding line which astronomers had for centuries been throwing into space touched bottom. The employment of the heliometer which Bessel introduced was the main source of our knowledge of the distances of stars until the end of the nineteenth century, and resulted in fairly satisfactory determination of the parallaxes of nearly one hundred stars. For the part of space nearest to us this survey is sufficiently complete for us to infer the average distances of the stars from one another—2½ to 3 parsecs. The parallax determinations of double stars of known orbits lead to the result that the masses of stars have not a very great range, but lie between forty times and one tenth of the mass of the sun.

When the absolute luminosities of the stars the distances of which have been measured are calculated, it is found that, unlike the masses, they exhibit a very great range. For example, Sirius radiates forty-eight times as much light as the sun, and Groombridge thirty-four only one hundredth part. This does not represent anything like the complete range, and Canopus, for example, may be ten thousand times as luminous as the sun. But among the stars near the solar system, the absolute luminosity appears to vary with the type of spectrum. Thus Sirius, of type A, a blue hydrogen star, is forty-eight times as luminous as the sun; Procyon of type F_5—bluer than the sun, but not so blue as Sirius—ten times; α Centauri, which is nearly of solar type, is twice as luminous. 61 Cygni of type K_5—redder than the sun—one tenth as luminous; while the still redder star of type Ma, Gr 34, is only one hundredth as luminous. In the neighborhood of the solar system one third of the stars are more luminous and two thirds less luminous than the sun. The luminosity decreases as the type of spectrum changes from A to M, *i. e.,* from the blue stars to the red stars.

These three results as to the density in space, the mass, and the luminosity have been derived from a very small number of stars. They show the great value of accurate determinations of stellar parallax. So soon as the parallax is known, all the other observational data are immediately utilizable. At the commencement of the present century the parallaxes of perhaps eighty stars were known with tolerable accuracy. Happily the number is now rapidly increasing by the use of photographic methods. Within the last year or two, the parallaxes of nearly two hundred stars have been determined and published. This year a committee of the American Astronomical Society, under the presidency of Professor Schlesinger, has been formed to coordinate the work of six or seven American and one or two English observatories. The combined program contains 1,100 stars, of which 400 are being measured by more than one observatory. We may expect results at the rate of two hundred a year, and

may therefore hope for a rapid increase of our knowledge of the stars within our immediate neighborhood.

VELOCITIES IN THE LINE OF SIGHT

The determination of radial velocities was initiated by Huggins in the early 'sixties, but trustworthy results were not obtained until photographic methods were introduced by Vogel in 1890. Since that time further increase in accuracy has been made, and the velocity of a bright star with sharp lines is determinable (apart from a systematic error not wholly explained) with an accuracy of $\frac{1}{4}$ kilometer per second. As the average velocities of these stars are between 10 and 20 kilometers a second, the proportional accuracy is of a higher order than can be generally obtained in parallax determinations or in other data of sidereal astronomy. A number of observatories in the United States and Europe, as well as in South America, the Cape, and Canada, are engaged in this work. Especially at the Lick Observatory under Professor Campbell's direction, the combination of a large telescope, a well-designed spectroscope and excellent climatic conditions have been utilized to carry out a bold program. At that observatory, with an offshoot at Cerro San Christobal in Chile, for the observation of stars in the southern hemisphere, the velocities of 1,200 of the brightest stars in the sky have been determined. Among the results achieved is a determination of the direction and amount of the solar motion. The direction serves to confirm the results from proper motions, but the velocity is only obtainable accurately by this method. This quantity, which enters as a fundamental constant in nearly all researches dealing with proper motion, is given by Campbell at 19.5 kilometers per second, or 4.1 times the distance of the earth from the sun per annum, though there is some uncertainty arising from a systematic error of unknown origin.

The observations of radial velocities have shown within what limits the velocities of stars lie and have given a general idea of their distribution. The most important result, and one of a somewhat surprising character, is that the mean velocities of stars, the motion of the sun being abstracted, increase with the type of spectrum. Thus the stars of type B, the helium stars, the stars of the highest temperature, have average radial velocities of only 6.5 kilometers per second; the hydrogen stars of type A have average velocities of 11 kilometers per second; the solar stars of 15 kilometers per second; while for red stars of types K and M it has increased slightly more to 17 kilometers per second. Further, the few planetary nebulæ—*i. e.*, condensed nebulæ with bright line spectra—have average velocities of 25 kilometers per second. There can be no question of the substantial accuracy of these results, as they are closely confirmed by discussions of proper motions. They are, however, very difficult to understand. On the face of it, there does not seem any reason why stars of a high temperature should have specially high velocities. A suggestion has been thrown out by Dr. Halm that as the helium stars have greater masses, these results are in accordance with an equi-partition of energy. But the distances of stars apart is so great that it seems impossible that this could be brought about by their interaction. Professor Eddington suggests that the velocities may be an indication of the part of space at which the stars were formed (*e. g.*, stars of small mass in outlying portions), and represents the kinetic energy they have acquired in arriving at their present positions.

The stars the radial velocities of which have been determined are, generally speak-

ing, brighter than the fifth magnitude, Fainter stars are now being observed. At the Mount Wilson Observatory, Professor Adams has determined the velocities of stars of known parallaxes, as there are great advantages in obtaining complete data for stars where possible. Extension of line-of-sight determinations to fainter stars is sure to bring a harvest of useful results, and a number of great telescopes are engaged, and others will shortly join in this important work.

PROPER MOTIONS

As proper motions are determined by the comparison of the positions of stars at two different epochs, they get to be known with constantly increasing accuracy as the time interval increases. The stars visible to the naked eye in the northern hemisphere were accurately observed by Bradley in 1755. Many thousands of observations of faint stars down to about 9.0 m. were made in the first half of the nineteenth century. An extensive scheme of reobservation was carried out about 1875 under the auspices of the Astronomische Gesellschaft. A great deal of reobservation of stars brighter than the ninth magnitude has been made this century in connection with the photographic survey of the heavens. For the bright stars all available material has been utilized and their proper motions have been well determined, and for the fainter stars this is being gradually accomplished.

Proper motions differ widely and irregularly in amount and direction. Herschel observed a tendency of a few stars to move towards one point of the sky, and attributed this sign of regularity to a movement of the solar system in the opposite direction. But puzzling differences given by different methods remained unexplained until the difficulty was resolved by Professor Kapteyn in a paper read before this section of the British Association at its meeting in South Africa ten years ago. He showed that the proper motions had a general tendency towards two different points of the sky and not towards one only, as would be expected if the motions of the stars themselves were haphazard, but viewed from a point in rapid motion. He concluded from this that there was a general tendency of the stars to stream in two opposite directions. It is interesting to notice that this great discovery was made by a simple graphical examination of the proper motions of stars in different regions of the sky, after the author had spent much time in examining and criticizing the different methods which had been adopted for the determination of the direction of the solar motion. The subject was brought into a clearer and more exact shape by the analytical formulation given to it by Professor Eddington, and after him by Professor Schwarzschild.

This star-streaming is corroborated by observations of velocities in the line of sight. It applies—with the exception of the helium stars—to all stars which are near enough for their proper motions to be determinable. We may say with certainty that it extends to stars at distances of two or three hundred parsecs; it may extend much further, but I do not think we have at present much evidence of this. Professor Turner pointed out that the convergence of proper motions did not necessarily imply movements in parallel directions, and suggested that the star-streams were movements of stars to and from a center. The agreement of the radial velocities with the proper motions seems to me to be opposed to this suggestion, and to show that star-streaming indicates approximate parallelism in two opposite directions in the motions of the stars examined. As the great majority of these stars are comparatively near to us, it is possible that this parallelism is mainly confined to them, and indicates the general directions

of the orbital motions of stars in the neighborhood. An attempted explanation on these lines, as on Professor Turner's, implies that the sun is some distance from the center of the stellar system.

A discovery of an entirely different character was made by Professor Boss in 1908. He spent many years in constructing a great catalogue giving the most accurate positions and motions of 6,200 stars obtainable from all existing observations. This catalogue, which was published by the Carnegie Institution, was intended as a preliminary to a still larger one which would give the accurate positions and motions of all the stars down to the seventh magnitude. In the course of this work Professor Boss found that forty or fifty stars scattered over a considerable region of the sky near the constellation Taurus were all moving towards the same point in the sky and with nearly the same angular velocity. He inferred that these stars were all moving in parallel directions with an equal linear velocity, and the supposition was verified, in the case of several of them, by the determination of their radial velocities. From these data he was able to derive the distance of each star and thus its position in space. The existence of a large group of stars, separated from one another by great distances, and all having the same motion in space, is a very remarkable phenomenon. It shows, as was pointed out by Professor Eddington, how small is the gravitational action of one star on another, and that the movement of each star is determined by the total attraction of the whole mass of the stars. Several other interesting moving clusters have been found since. For all the stars belonging to these clusters, the distances have been found, and from them luminosities and velocities of individual stars, particulars which are generally only obtainable for stars much nearer to us.

Proper motions are the main source of our knowledge of the distances of stars which are beyond the reach of determination by annual parallax. If a star were known to be at rest its distance could be calculated from the shift of its apparent position caused by the translation of the solar motion. As the solar system moves 410 times the distance of the earth from the sun in a century, this gives a displacement of 1″ for a star at the distance of 500 parsecs. This method has been applied by Kapteyn to determine the distances of the helium stars, as their velocities are sufficiently small to be neglected in comparison with that of the solar system. But generally it is only possible to find the mean distances of groups of stars of such size that it may be assumed that the peculiar motions neutralize one another in the mean. For example, the average distance of stars of type A, or stars of the fifth magnitude, or any other group desired may be found. In this way Kapteyn has found from the Bradley stars that the mean parallax of stars of magnitude m is given by the formula

$$\log. \pi_m = -1.108 - 0.125\, m.$$

In conjunction with another observational law which expresses the number of stars as a function of the magnitude, this leads to a determination of the density of stars in space at different distances from us, and also of the "luminosity law," *i. e.*, the percentage of stars of different absolute brightness. Professors Seeliger and Kapteyn have shown in this way that there is a considerable falling off of star-density as we go further from the solar system. It seems to me very necessary that this should be investigated in greater detail for different parts of the sky separately. A general mathematical solution of general questions which arise in the treatment of astronom-

ical statistics has been given by Professor Schwarzschild. His investigations are of the greatest value in showing the exact dependence of the density, luminosity and velocity laws on the statistical facts which can be collected from observation. The many interesting statistical studies which have been made are liable to be rather bewildering without the guidance furnished by a general mathematical survey of the whole position.

When the proper motions are considered in relation to the spectral types of the stars, the small average velocities of the hydrogen stars and still smaller ones of the helium stars found from line-of-sight observations are confirmed. If stars up to a definite limit of apparent magnitude, say, to 6.0 m., or between certain limits, say 8.0 m. and 9.0 m., are considered, then the solar stars are found to be much nearer than either the red or the blue stars. Thus both red and blue stars must be of greater intrinsic luminosity than the solar stars. As regards blue stars, this agrees with results given by parallax observations. But the red stars appear to consist of two classes, one of great and one of feeble luminosity, and it does not seem that a sufficient explanation is given by the fact that a selection of stars brighter than any given apparent magnitude will include the very luminous stars which are at a great distance, but only such stars of feeble luminosity as are very near.

The significance of these facts was pointed out by Professor Hertzsprung and Professor Russell. They have a very important bearing on the question of stellar evolution, a subject for discussion at a later meeting this week. From the geometrical point of view of my address these facts are of importance in that they help to classify the extraordinarily large range found in the luminosities of stars. Putting the matter somewhat broadly, the A stars, or hydrogen stars, are on the average intrinsically 5 magnitudes brighter than the sun, whilst the range in their magnitudes is such that half of them are within $\frac{3}{4}$ magnitude of the mean value. The stars of type M, very red stars, are of two classes. Some of them are as luminous as the A stars, and have a similar range about a mean value 5 magnitudes brighter than the sun. Others, on the contrary, have a mean intrinsic brightness 5 magnitudes fainter than the sun and with the same probable deviation of $\frac{3}{4}$ magnitude. Between the types M and A there are two classes the distance apart of which diminishes as the stars become bluer. The facts in support of this contention are very forcibly presented by Professor Russell in *Nature* in May, 1914. If this hypothesis is true, and it seems to me there is much to be said in its favor, then the apparent magnitude combined with the type of spectrum will give a very fair approximation to the distances of stars which are too far away for their proper motions to be determinable with accuracy.

In dealing with the proper motions of the brighter stars, the sky has been considered as a whole. Now that the direction and amount of the solar motion are known, we may hope that, as more proper motions become available, the different parts of the sky will be studied separately. In this way we shall obtain more detailed knowledge of the streaming, and also of the mean distances of stars of different magnitudes in all parts of the sky, leading to a determination of how the density of stars in space changes in different directions. A second line of research which may be expected to give important results is in the relationship of proper motions to spectral type. There is in preparation at Harvard College by Miss Cannon, under Professor Pickering's direction, a catalogue giving the type of

spectrum of every star brighter than the ninth magnitude. It would be very desirable to determine the proper motions of all these stars. If all the material available is examined it should be possible to do this to a very large extent.

PHOTOMETRY AND COLOR

For the more distant parts of the heavens proper motions are an uncertain guide, and we must depend on what can be learned from the light of the stars by means of stellar photometry, determinations of color, and studies of stellar spectra. Speaking generally, we attempt to discover from the nearer stars sufficient about their intrinsic luminosities to enable us to use the apparent magnitude as an index of the distances of the stars which are further away. The most striking example is found in Professor Hertzsprung's determination of the distance of the small Magellanic cloud. From a knowledge of the characteristics of the Cepheid variables found in this cloud by Miss Leavitt, and their apparent magnitude, he deduced the distance of the cloud as 10,000 parsecs.

Much attention has been given of late years to stellar photometry. In 1899 Professor Pickering published the Revised Harvard Photometry giving the magnitudes of all stars brighter than 6.5 m. In 1907 Messrs. Müller and Kempf completed a determination of 14,199 stars of the northern hemisphere brighter than 7.5 m. In 1908 a catalogue of 36,682 stars fainter than 6.5 m. was published at Harvard. These determinations derive additional importance as they give the means of standardizing estimates of magnitude made by eye, particularly the many thousands of the Bonn Durchmusterung.

By the labors of Professor Pickering and his colleagues at Harvard, Professor Schwarzschild, Professor Parkhurst at Yerkes, Professor Seares at Mount Wilson, and others, the determinations of the magnitudes of stars by photography has made rapid strides. As yet no complete catalogues of photographic magnitude corresponding to the Revised Harvard Photometry have been published, though considerable parts of the sky and special areas, such as the Pleiades, have been carefully studied. The determination of the photographic magnitudes of any stars which may be required is, however, a comparatively simple matter when the magnitudes of sufficient standard stars have been found. A trustworthy and uniform scale has been to a large extent secured by the use of extra-focal images, gratings and screens in front of the object glass, and the study of the effects of different apertures and different times of exposure.

At Harvard and Mount Wilson, standard magnitudes of stars near the north pole have been published extending to nearly the twentieth magnitude. In the part of the range extending from 10.0 m. to 16.0 m. these agree very satisfactorily. There is, however, a difference of 0.4 m. in the scale between 6.0 m. and 10.0 m. which needs to be cleared up.

A uniform and accurate scale of magnitude is of fundamental importance in counts of the numbers of stars. Such counts aim at the determination of two things: (1) how the numbers vary in different parts of the sky, and (2) what is the ratio of the number of stars of each magnitude to that of the preceding magnitude in the same area of the sky. The counts of stars from the gauges of Sir William and Sir John Herschel, those of the stars contained in the Bonn Durchmusterung, those made by Professor Celoria, and the recent counts of the Franklin-Adams plates by Dr. Chapman and Mr. Melotte, all agree in showing a continuous increase of stars as we proceed

from the pole of the galaxy to the galaxy itself. The importance of this fact is that it shows a close connection between the Milky Way and the stars nearer to us. The Milky Way is not a system of stars beyond the others, but is the primary feature of our "island universe."

Photometric observations have acquired additional importance from the differences between photographic and visual magnitudes. The ordinary plate is more sensitive to blue light than the eye, and the difference between the photographic and visual (or photo-visual) magnitude of a star is an index of the color. The color index is found by observation to be related very closely to the type of spectrum. Professor Seares has shown from the color indices that as the stars become fainter they become progressively redder. Professor Hertzsprung has found the same thing by the use of a grating in front of the object glass. Among stars of 17.0 m. visual magnitude, Seares found none with a color index less than 0.7; this is approximately the color index of a star of solar type, *i. e.*, near the middle of the range from blue stars to red stars.

There are three ways in which this may occur. The stars may be bright but very distant red stars; or they may be faint red stars, like those in the immediate neighborhood of the sun; or there may have been an absorption of blue light. It is not possible to say in what proportion these causes have contributed. The red stars of 9.0 m. and 10.0 m. are nearly all very luminous but distant bodies, but it seems likely that stars of 17.0 m. will contain a greater proportion of stars of small luminosity.

The absorption of light in space is very small, and as yet imperfectly determined. Professor Kapteyn and Mr. Jones, by comparing the color indices of stars of large and small proper motion, make the difference between the absorption of photographic and visual light as 1 m. in 2,000 parsecs. The question has been examined directly by Professor Adams, who has obtained spectra of near and distant stars which are identical as regards their lines, and has examined the distribution of the continuous light. This direct method of comparison showed that the more distant star was always weaker in violet light. But as both these investigations show that very luminous stars are intrinsically somewhat bluer than less luminous stars of the same spectral type, the two causes require further research for their disentanglement. The question is of importance, as it may serve in some cases to determine the distances of very remote bodies the type of spectrum of which is known.

It must be admitted that we are as yet very ignorant of the more distant parts of the "island universe." For example, we can make little more than guesses at the distance of the Milky Way, or say what part is nearest to us, what are its movements, and so on. But, nevertheless, the whole subject of the construction of the heavens has been opened up in a remarkable manner in the last few years. The methods now employed seem competent to produce a tolerably good model showing the coordinates and velocities of the stars as well as their effective temperatures and the amount of light they radiate. Industry in the collection of accurate data is required, along with constant attempts to interpret them as they are collected. The more accurate and detailed our knowledge of the stellar system as it is now, the better will be our position for the dynamical and physical study of its history and evolution.

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